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Inequality Conditions for Critical Velocity Ionization Space Experiments

Shu T. Lai, *Senior Member, IEEE*, and Edmond Murad

***Abstract*—This is a compilation of various parametric conditions for the critical ionization velocity (CIV) process to occur in the ionosphere.**

I. Introduction

Tests of critical ionization velocity (CIV) in the laboratory have repeatedly demonstrated its occurrence with ease, while the space experiments have yielded, at best, mixed results (see, for example [1]). Whether or not CIV occurs in space and how easily it is initiated have important implications in the Space Shuttle environment (see, for example, [2]). In order to demonstrate CIV clearly in space, it is necessary to consider the optimal conditions under which CIV may occur.

Although Alfvén originally suggested in the CIV concept that rapid ionization would occur when the critical ionization velocity, V_*, is exceeded, transferring this concept into an actual positive space experiment requires that careful attention be paid to determining the details of such experiments. In view of the increasing number of CIV space experiments conducted or planned in recent years, it is useful to compile the main inequality conditions which have to be satisfied for CIV to be triggered. This paper is not meant to be an exhaustive survey, but it aims at discussing the most important and salient aspects of CIV.

II. Beam Velocity

Alfvén [3], [4] postulated that when the relative velocity, V, between a neutral gas and a magnetized plasma exceeds a critical value, V_*, rapid ionization occurs. Alfvén [3], [4] gave a formula for the critical ionization velocity, V_*, as

$$V_* = \sqrt{2e\varphi/M}. \tag{1}$$

where $e\varphi$ is the ionization energy and M the mass of a neutral atom or molecule. Subsequent laboratory CIV experiments (e.g. [5]) have shown that rapid ionization occurs at values often slightly higher than V_*. Formisano *et al.* [6] introduced an empirical efficiency factor, η, into Alfvén's formula (eq. (1)) to account for energy loss by various (sometimes intangible) mechanisms:

$$V_* = \sqrt{2e\phi/M\eta}. \tag{2}$$

where η is smaller than unity. Equation (2) replaces (1) if η is significant. For critical velocity ionization to occur, it is necessary for the velocity V to exceed V_*:

$$V > V_*. \tag{3}$$

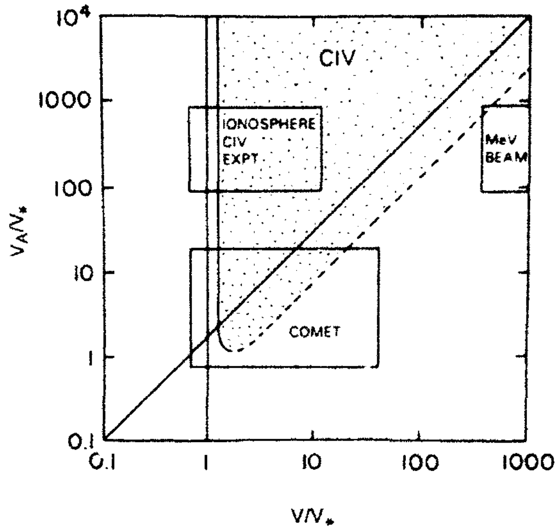

Fig. 1. Parametric domain of CIV (adapted from [9]).

Papadopoulos [7] pointed out that if the velocity V is so fast that it exceeds a critical value V_s, electromagnetic modes may be excited:

$$V_s = (1 + \beta_e)^{1/2} V_A. \tag{4}$$

where $\beta_e \sim nkT/B^2$ and V_A is the Alfvén velocity. These electromagnetic modes tend to drain away energy [8]. Indeed, Machida and Goertz [9] and Goertz *et al.* [10] have obtained numerical simulation results demonstrating the suppression of CIV when $V > V_s$ with the modified two-stream instability and electron heating becoming inefficient. Fig. 1 shows a parametric domain of CIV with boundaries of $V > V_*$ and $V < V_s$. Laboratory measurements [11] on CIV of H_2O have confirmed the electromagnetic effect in quenching CIV (Fig. 2).

Thus, for CIV to occur, the beam velocity criterion is

$$V_s > V > V_*. \tag{5}$$

III. Townsend's Criterion

Townsend's criterion [12] for discharges states that, in order to sustain a discharge, an electron has to generate at least one electron during its residence time in the interaction region. In typical CIV space experiments, a beam or cloud of neutral

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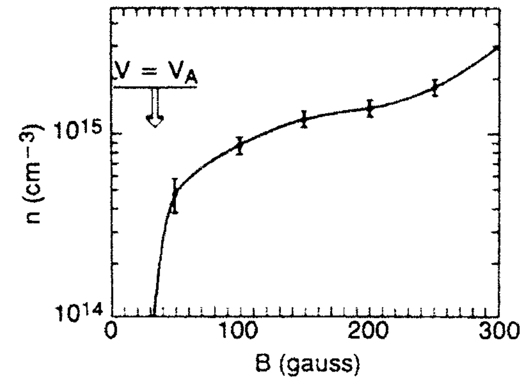

Fig. 2. Ionization density n as a function of magnetic field B in a laboratory CIV experiment (from [11]).

gas is injected across the ambient magnetic field. The beam, or cloud, diverges as it propagates. The ionization time, τ_i, is given by

$$\tau_i(x) = 1/[n(x)\sigma(v_e)v_e]. \tag{6}$$

where x is the distance from the exit point, n the neutral gas density, σ the cross section of electron impact ionization, and v_e the electron velocity. To satisfy Townsend's criterion, the ionization time, τ_i, has to be shorter than the electron residence time, τ_e. In the literature, two residence times have been considered. They are the electron transit time [2] and the cloud transit time [13], [14]. These two versions will be discussed as Townsend's conditions I and II respectively in the following.

Townsend's Condition I

Consider a conical beam of neutral gas. The neutral density, $n(x)$, drops as the beam expands:

$$n(x) = N_0/[V\pi x^2 \tan^2(\phi/2)]. \tag{7}$$

where N_0 is the release rate, V the beam velocity, and ϕ the cone angle. The electron transit time, $\tau_e(x)$, increases with x because of the beam divergence:

$$\tau_e(x) = 2x\tan(\phi/2)v_e^{-1} \tag{8}$$

Townsend's condition in this case is

$$\tau_e(x) > \tau_i(x). \tag{9}$$

which yields a critical distance, x_1, beyond which Townsend's condition is not satisfied. This implies that CIV can only occur within a distance $x < x_1$, which is given by

$$x_1 = 2N_0\sigma/[V\pi\tan(\phi/2)]. \tag{10}$$

Fig. 3 shows the critical distance as a function of N_0. Equation (6) is valid for a steady-state continuous beam only or for a gas cloud of length d as long as $d > x_1$.

Consider next a gas cloud of length d with $d < x_1$. The density, $n_d(x)$, of the cloud can be modeled as

$$n_d(x) = 3N/[4\pi(V_r t)^3]. \tag{11}$$

where N is the total number of neutrals at $t = 0$, V_r is the radial expansion velocity, the cloud length $d = V_r t$, and

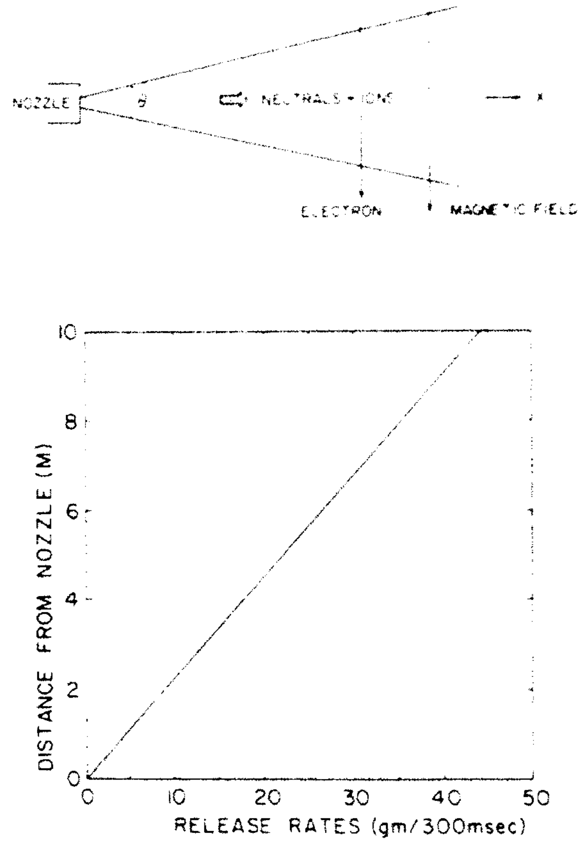

Fig. 3. Townsend distance x_1 in conical beam model (from [2]).

the distance from the exit point is $x = Vt$. In this case, Townsend's condition (eq. (9)) yields a critical distance x_d:

$$x_1 = x_d = (V/V_r)(3N_0/2\pi)^{1/2}. \tag{12}$$

Fig. 4 shows the Townsend critical distance computed for CRIT II and CRRES-like experimental situations.

We remark that both of the Townsend I results (10) and (12), are independent of the electron velocity, v_e. Therefore, even if the electrons are subsequently slowed down by ion space charge, the result is the same. However, if the effective distance traveled by the electrons becomes longer, due to scattering for example, then the requirements (10) and (12) would become less stringent.

Townsend's Condition II

In CIV, electron energization, or heating, occurs in a time interval τ_H. As a neutral cloud propagates forward across the magnetic field, the electrons being energized are more or less tied down by the field lines. Therefore the electrons lag behind the ions, which are almost unmagnetized for time shorter than a quarter of the ion cyclotron period. If the cloud dimension d is short, the electrons may lag behind the cloud with insufficient heating. Therefore, the following condition [18] is necessary for CIV:

$$\tau_d \tau_H^{-1} > 1, \tag{13}$$

where

$$\tau_d = d/V \tag{14}$$

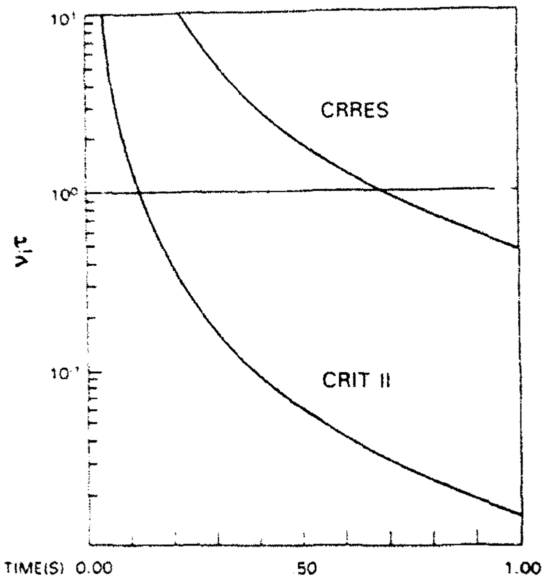

Fig. 4. Calculated critical distance x_1 for CRIT-II and CRRES like releases. The one for CRIT-II used a random velocity of ± 1.5 km/s and a main velocity of 7 km/s. The one for CRRES used a main velocity of 11 km/s and a random velocity of ± 1 km/s (from [16]).

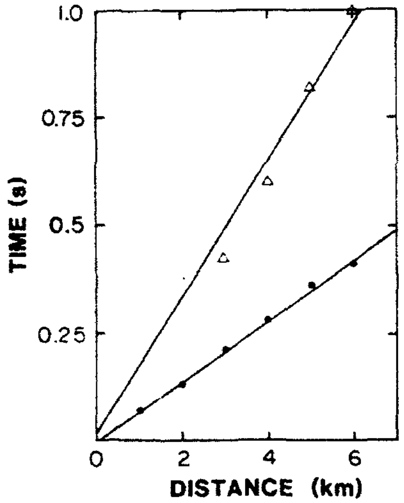

Fig. 5. Pulse expansion in the *Star of Lima* experiment. The points are the locations of pulse heights estimated from *Torbert's* data [17] (from [18]).

is the transit time of the cloud across a magnetic field line. Fig. 5 illustrates the transit of an expanding cloud in a CIV space experimental situation.

For example, if an initially δ-function pulse cloud is injected and the cloud expands according to $d = V_r t$, then (13) requires

$$t > (V/V_r)\tau_H \tag{15}$$

or

$$x > x_2 = (V^2/V_r)\tau_H, \tag{16}$$

which implies CIV cannot occur at distances too near the exit point. Combining Townsend's conditions I and II, we find that CIV has to occur between the critical distances x_1 and x_2:

$$x_1 > x > x_2. \tag{17}$$

TABLE I
Townsend's Conditions

	τ_{H1}	τ_{H2}	τ_i
τ_e = electron transit time			Townsend I (Eq. (9))
τ_d = cloud transit time	Brenning [14] Axnäs [15]	Townsend II (Eq. (13))	Haerendel [13]

Before closing this section, two remarks will be given. The first remark concerns the heating time, τ_H. In the above discussion (eqs. (13)–(17)), we have not specified τ_H, which depends on the heating situation. If the electrons are heated from an initial state in which there are a stationary ambient plasma and some ion seeding mechanism which builds up an ion beam density from zero as considered by Brenning [14] and Anxäs [15], τ_H is extremely sensitive to the seeding rate and the initial electron temperature. We denote this type of τ_H as τ_{H1}. If, on the other hand, the electrons are heated when an ion beam is already formed, as considered by Tanaka and Papadopoulos [31], a good estimate of τ_H is $30/\omega_{LH}$ according to computer simulations [31]. We denote this type of τ_H as τ_{H2}. For a continuous injection as considered in this paper, it is likely that the latter situation [31] is more relevant. In the rest of the paper, τ_H is τ_{H2}.

The second remark concerns another version of Townsend's criterion. Haerendel [13] used ionization time, τ_i, in place of heating time, τ_H, in (13). This places much milder restrictions on the CIV process, and will not be considered. For experimental designs, it is more cautious to use a restrictive criterion (eq. (13)). Table I summarizes the combinations discussed in the two remarks.

IV. Magnetic Field Strength

Brenning [19] proposed on theoretical grounds an upper limit to B (eq. (18)) for CIV to occur. Equation (18), to our knowledge, has not yet been tested experimentally:

$$\omega_p(n_e)/\omega_e(B) > (m/M)^{1/2} \tag{18}$$

Here ω_p and ω_e are the plasma and electron gyrofrequencies respectively, m the electron mass, M the ion masses, and n_e the plasma density.

Brenning [8] pointed out that (4) gives a lower limit of magnetic field. Brenning [19] showed experimentally an absence of CIV for a weak magnetic field. The absence of CIV in Brenning's experiment [19] agrees completely with the lower B field limit given by (4).

Suppose for a given set of experimental parameters, the value of the magnetic field satisfying (18) is B_1 and that satisfying (4) is B_2. Then, the range of magnetic field B for CIV to occur is limited by

$$B_1 > B > B_2. \tag{19}$$

where B_1 is given by (18) and B_2 by (4).

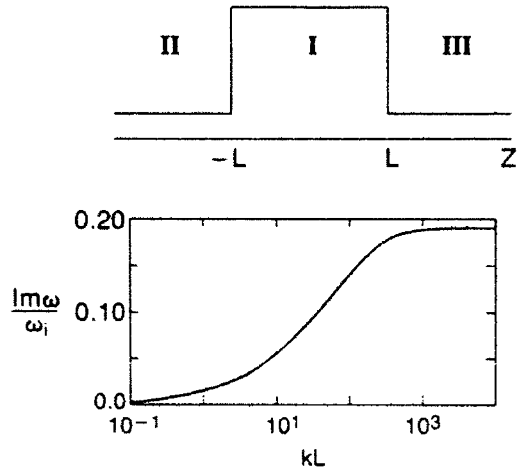

Fig. 6. The growth rate, Im ω, decreasing as kL decreases, in a simple density profile beam model (from [22]).

V. Beam Width

Large beam width L may favor CIV in two ways. Firstly, larger beam width implies that the residence time τ_e of an electron is longer:

$$\tau_e = L/v_e, \tag{20}$$

where v_e is the electron velocity along the magnetic field direction. Longer τ_e, in turn, implies higher probability of electron impact ionization in the beam and hence better chance for Townsend's condition I (eq. (9)) to be satisfied. Besides, escape of hot electrons implies not only a reduction in the number of electrons but also energy loss. Therefore, the wider the beam, the better the chance for CIV. Secondly, Newell [20] and Kelley *et al.* [21] have suggested that in order for the modified two stream instability to be efficient, it is necessary for the beam to be wide enough to accommodate the parallel component of the lower hybrid wavelength:

$$L > \lambda_{\parallel}. \tag{21}$$

A simple theoretical square density model [22] has been found to yield a monotonically decreasing function of the instability growth rate Im ω/ω_i, where ω_i is the ion plasma frequency, as a function of decreasing beam width L (Fig. 6). The theoretical result agrees with the suggestions of Newell [20] and Kelley *et al.* [21].

In typical CIV space experiments, the value of $\lambda_{\parallel}$ is of the order of km [21]. For a diverging beam with a longitudinal velocity of 8 km/s and a radial velocity of 1 km/s, for example, the efficiency for CIV is reduced by this effect in the early 1 second period or 8 km distance. Conceivably, the proposed CIV process in the primordial solar system [3] can satisfy (21) because the dimension L was astronomically large.

We remark that violation of the condition $L > \lambda_{\parallel}$ (eq. (21)) does not preclude CIV although it would reduce the instability growth rate.

Finally, we remark that there is no known upper limit on the beam width L for CIV to occur. The efficiency of CIV increases monotonically with the width of the beam. If CIV can occur in the spacecraft environment, the environment of the space station with its large size (order of km) may be a more likely place for CIV to occur.

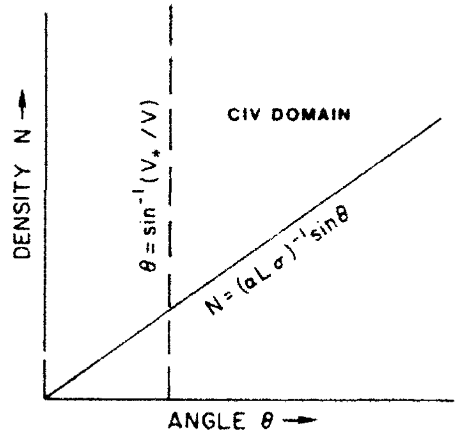

Fig. 7. CIV parametric domain: it shows that 90° may not be optimal (from [2]).

VI. Pitch Angle

We discuss here two aspects: 1) electron escape and 2) electron energization. In the first, we consider the increase in the effective distance, L, for an electron traveling along $\boldsymbol{B}$, or in the plane of $\boldsymbol{B}$ and $\boldsymbol{E} \times \boldsymbol{B}$. The magnetic pitch angle θ of a beam need not be 90°:

$$L(\theta) = L/\sin\theta, \tag{22}$$

where $L \equiv L(\theta = 90^\circ)$. However, the beam kinetic energy E available for energizing the instability waves and electrons would be reduced accordingly:

$$E(\theta) = E(\theta = 90^\circ)\sin^2\theta, \tag{23}$$

where $E(\theta = 90^\circ) = (1/2)MV^2$. Since τ_e (eq. (20)) has to be greater than τ_i (eq. (9)), and $E(\theta)$ has to be greater than $e\phi$ (eq. (1)), one obtains from (1), (9), (20), (22), and (23) an inequality [2]:

$$L\sigma n > \sin\theta > V_*/V, \tag{24}$$

where L, σ, n, V_*, and V have been defined already. Fig. 7 shows a parametric domain of CIV as limited by this aspect.

With regard to electron energization, Goertz *et al.* [23] have emphasized that, in the heating process of electrons by means of the modified two-stream instability, $\theta = 90^\circ$ may not always be optimum for two reasons. The first is that resonance wave–particle heating at an electron tail can only heat a small electron population to even higher energy. It is better to heat just below the tail, where the population is higher, so that more electrons will be heated. The electrons heated in such a way then become hot electrons as they migrate into the tail distribution. Therefore, for a given beam energy, the pitch angle θ should be adjusted so that the wave phase velocity is just below the tail in order to achieve optimum heating [24]. The second reason is that the cross section σ of ionization features a maximum around 70 to 100 eV for most elements. If the beam has too much kinetic energy, the electrons may be heated to an energy too high for optimum ionization. Adjusting

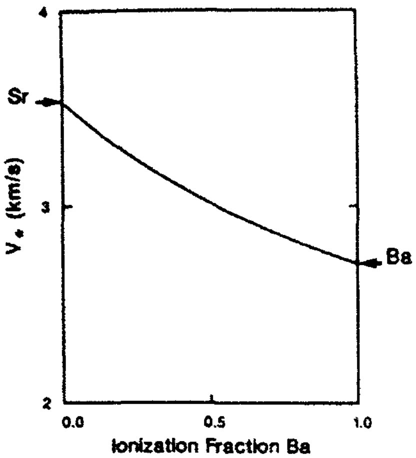

Fig. 8. Critical ionization velocity in a mixture of Sr and Ba (from [25]).

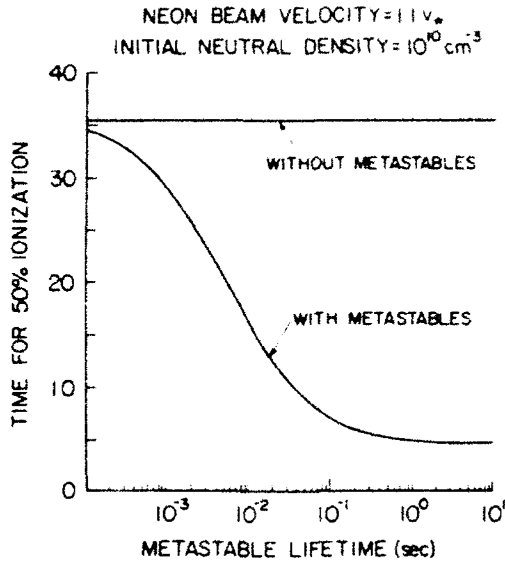

Fig. 9. Effect of radiative lifetime of the metastable state on the onset of ionization (from [27]).

θ may yield a hot tail at the peak σ range. However, we must remark that $\langle \sigma v_e \rangle$ is often approximately constant in many cases. Thus, this reason is less important. Also, in order to achieve maximum ionization rate for a given available energy W, one maximizes $\langle \sigma v_e \rangle / W$, where $W = (1/2)mv_e^2$ for monoenergetic electrons. The maximization condition gives $d\sigma/dv = \sigma/v$, which requires energies below the maximum of $\sigma(v)$.

VII. Mixture of Species

Anxäs [5] reported experimental results which show only one critical ionization velocity in a binary mixture of species, while Lai *et al.* [25] reported a theoretical analysis of a general mixture of species. In a mixture of species with a given velocity distribution $f(V)$ and various masses and ionization potentials, some species may act as energy sources while others as energy sinks. Depending on the parameter domains, it is possible to have single or multiple species undergoing CIV. A generalized Alfvén CIV formula, which represents the energy budget, has been suggested [25]:

$$\Sigma_i \nu_i \int dV \left[(1/2)M_i V^2 - e\phi_i\right] f(V) \geq 0. \tag{25}$$

where i labels the species, V the neutral velocity, and ν the fractional ionization. Fig. 8 shows this energy budget for a binary mixture of Sr and Ba.

Depending on the velocity V and the extent of the hot tail of electrons, single and multiple critical ionization velocities may exist [25]. When the number of species is 1, (25) reduces to Alfvén's formula (eq. (1)); when the number is 2, (25) reduces to Axnäs's formula [5].

To illustrate this treatment, we consider the Space Shuttle exhaust, which is a mixture of several species [2]. The main species are H_2O, N_2, H_2, CO, and CO_2, their mole fractions being 0.33, 0.31, 0.16, 0.13, and 0.042 respectively [25]. In the simplest case, all species travel at the same velocity V. The critical ionization velocity calculated using (25) [25] is very near the classical Alfvén critical velocity of $H_2O(V_* \approx 11.6$ km/s$)$. As another example, a square shaped velocity distribution $f(V) = 11.2 \pm \Delta V$, would require $\Delta V \geq \pm 5.2$ km/s in order to satisfy the energy budget and achieve CIV.

VIII. Metastable States

As discussed earlier, hot electrons, which are in the tail of the Maxwellian distribution, are much less abundant than warm electrons, which are just below the tail. When the energy budget is tight, these electrons alone may have difficulty in triggering and sustaining a CIV process. If the lower energy (and more abundant) electrons can also participate in ionization, it would be easier to achieve CIV. In discharge tube studies, the importance of metastable states in ionization and gas breakdown has been established (e.g. [26]). In a two-step ionization process via the metastable state, each step requires an energy less than $e\phi$, the ground-state ionization energy. Therefore, metastable states may foster CIV, especially under tight budget situations. Lai *et al.* [27] and McNeil *et al.* [28] have demonstrated that metastable states can indeed help CIV provided that the metastable state lifetime, τ_M, is long enough. For example, in a simple model of neonlike CIV discharge [27], inclusion of metastable states would make at least 50% faster ionization if $\tau_M > 8 \times 10^{-3}$ s (Fig. 9).

To estimate the critical τ_M, one equates the metastable state lifetime, τ_M, to the ionization time per atom for the transition $(m \rightarrow i)$ from a metastable state to the ionizing state. One obtains

$$\tau_M > 1/(n_e \sigma_{mi} v_e). \tag{26}$$

where n_e and v_e are the electron density and velocity, and σ_{mi} the cross section of the transition $(m \rightarrow i)$. Larger values of lifetime τ_M, electron velocity, electron density, and cross section σ_{mi} would favor metastable state ionization.

IX. Mass Loading

Haerendel [13], [29] pointed out that the beam ions, traveling with a velocity V, inevitably impart momentum to the

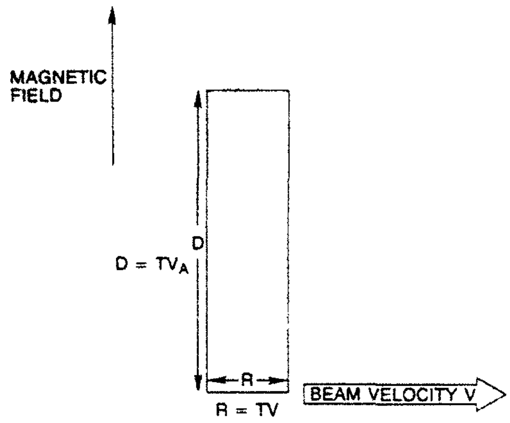

Fig. 10. A conceptual picture of momentum coupling of CIV in space. The beam travels for a distance R while the Alfvén waves a distance D.

ambient ions. As a result, the ambient ions, together with the corresponding magnetic flux tube, move forward, reducing the relative velocity, V_r, between the beam and the ambients. The phenomenon was called mass loading [13], [29]. A simple estimate of the critical beam density, above which mass loading becomes significant, can be obtained as follows.

Consider a beam of dimension R. Following Haerendel [13], [29], we assume that the length D of the magnetic flux tube involved in time T is given by

$$D = TV_A. \tag{27}$$

where V_A is the Alfvén velocity, and T the time required for the beam to traverse the flux tube (Fig. 10) such that

$$R = TV. \tag{28}$$

If the flux tube travels with a fraction s_a of the beam velocity V, we equate tne momenta lost by the beam and gained by the flux tube:

$$M_b n_b R(1 - s_b) = 2 M_a n_a R(V_A/V) s_a. \tag{29}$$

where the subscripts a and b denote ambient and ion beam respectively, s_b is the fractional slowdown of the initial beam velocity, and the 2 is for two flux tubes (upper and lower). From (29), we obtain a critical beam density n_b:

$$n_b = 2n_a \frac{M_a}{M_b} \frac{V_A}{V} \left(\frac{s_a}{1 - s_b} \right). \tag{30}$$

If the flux tube and the injected cloud gets a common velocity which is a fraction s of the initial beam velocity, $s = s_a = s_b$. We obtain a critical beam density at which $s = s_a = s_b = 0.5$ (i.e., the injected beam is braked to half its initial velocity):

$$n_b = 2n_a \frac{M_a V_A}{M_b V} \tag{31}$$

or

$$n_b = \frac{B}{M_b V} \sqrt{\frac{n_a M_a}{\pi}}. \tag{32}$$

Remarkably, mass loading implies that higher ambient plasma density favors CIV. If the altitude and therefore M_a remain approximately constant while the ambient plasma density, n_a, varies in day and night or solar cycles, (30) or (32) imply

$$n_b \propto \sqrt{n_a}.$$

which means higher n_a allows higher critical beam density n_b.

X. An Example of Multiple Inequalities

As an exercise, we consider a composite case in which several of the instabilities discussed are involved. We consider the scenario of a hypothetical space CIV experiment, in which a xenon gas is released from a satellite traveling at 7.4 km/s across the ambient magnetic field in the ionosphere. We assume the following initial conditions:

Gas pressure, p, in storage chamber = 10 atmospheres;
Gas temperature, T, in storage chamber = 273°K;
Radius of exit aperture = 0.25 cm;
Beam half cone angle $\phi/2 = 30°$;
Gas is pulsed in a sequence of 10 s, 1 s, and a shorter one.

The first inequality to be used is (5). At about 500 km altitude, the Alfvén velocity, V_A, for oxygen is about 700 km/s, and $\beta_e \approx 2 \times 10^{-5}$ [30]. Thus, (4) gives $V_c \approx V_A \approx$ 700 km/s for oxygen or about 240 km/s for Xe. As long as the xenon beam velocity is between 240 km/s and 4.225 km/s approximately, we expect the velocity requirement (eq. (5)) for CIV to be fulfilled.

We now use the second inequality (eq. (17)). From gas kinetic considerations, the initial gas velocity, V, is given in the spacecraft frame of reference by

$$V = (8kT/\pi M)^{1/2} = 210 \text{ m/s}. \tag{33}$$

where M is the molecular weight. The initial mass density ρ is a function of pressure p:

$$p = \rho V^2/3. \tag{34}$$

The mass release rate R is given by $R = VA\rho$, where A is the aperture area. The molecular release rate $N_o = R/M$. With these conditions, the first Townsend distance x_1 (eq. (10)) in the spacecraft frame of reference becomes

$$x_1 = 1.3(Ap/kT)\sigma. \tag{35}$$

Remarkably, (35) is independent of the molecular weight M of the gas species. In this sense, (38) is a *universal formula* for the "Townsend I" distance x_1. Taking a cross section $\sigma - 10^{-16}$ cm^2, (38) gives $x_1 \approx 66$ m from the exit point. For example, if there are several gas releases with different molecular masses, the universal formula (eq. (35)) yields the same "Townsend I" distance for all releases provided that the cross section σ is the same.

For a pulse of 1 second duration, the pulse length d is 0.21 km from the exit point. Assuming that the ambient magnetic field is stationary in the space frame, the time τ_d for a field line to sweep through the pulse is given by

$$\tau_d = 0.21/(7.4 + 0.21) = 27 \text{ ms}.$$

Suppose the electron heating time, τ_H, is given by $30/\omega_{LH}$ [31] and $\omega_{LH}(\mathrm{Ba})$ is 1034 Hz [30]; we have $\tau_H(\mathrm{Xe}) \approx$

TABLE II
INEQUALITIES

Parameter	Inequality	Equation
Beam velocity, V	$V_s > V > V_*$	5
Distance, x	$x_1 > x > x_2$	17
Magnetic field, B	$B_1 > B > B_2$	19
Beam width, L	$L > \lambda_\parallel$	21
Beam angle, θ	$L\sigma n > \sin\theta > V_*/V$	24
Fractional ionization, ν_i	$\sum_i \nu_i \int dV [(1/2)M_i V^2 - e\phi_i] f(V) \geq 0$	25
Metastable lifetime, τ_M	$\tau_M > 1/(n_e \sigma_{mi} v_e)$	26
Beam ion density, n_b	$n_b < 2n_a(M_a/M_b)(V_A/V)$	31

27 ms, which happens to equal τ_d. Thus, the 1 second pulse may marginally satisfy the Townsend II criterion (eq. (13)). The shorter pulse ejected later will not satisfy (13) and therefore will not undergo CIV.

Consider next the plasma density $n_e \approx 2.5 \times 10^5$/cc; here (18) yields $B_1 \approx 800$ G for Xe$^+$. In the ionosphere, B is typically 0.22 G. Therefore there is no difficulty in satisfying $B_1 > B$. As for the second inequality of (4), we observe that since $\beta \approx 2 \times 10^{-5}$ in the ionosphere [30], it takes an ambient magnetic field five orders of magnitude weaker to have a significant effect. Therefore, the magnetic field inequality (19) is satisfied easily in CIV space experiments.

In order to satisfy (21), the conical pulse has to travel for at least 6 s before its transverse dimension L reaches 1 km approximately. Prior to 6 s, the dimension L is too small for the full efficiency of the modified two-stream instability growth rate to take place. Failure to satisfy (21) does not necessarily rule out CIV although the efficiency is reduced.

To illustrate the utility of (24), suppose we wish to have CIV at $x = 70$ m, which is located just beyond the Townsend I distance ($x_1 \approx 66$ m), which is obtained by assuming perpendicular propagation (i.e., $\theta = 90°$). Equation (7) gives $n(x) = 1.2 \times 10^{12}$/cc. The transverse distance at x is $L = 80.8$ m. The first inequality of (24) gives $L\sigma n = 0.972 > \sin\theta$, restricting θ to be below 76°, the value for σ being taken as 10^{-16} cm^2. The second inequality of (24) requires that the beam velocity V exceeds 4.35 km/s to achieve CIV for Xe. This value is slightly higher than the normal xenon CIV value (4.23 km/s).

Returning to the scenario, we now consider metastable states. Xenon has two metastable states, one of which ($6s[3/2]_2$) has a lifetime τ_M of 150 s at 8.32 eV [32]. Ionization from a metastable state may help CIV. However, if a metastable state is not ionized fast enough, it may decay to a lower state with loss of energy in the form of radiation. To estimate a critical electron density n_e, we use (26), which gives

$$n_e > 1/(\tau_M \sigma_{mi} V_e). \tag{36}$$

Using the data of Cartwright *et al.* [33], the cross section σ_{mi} has been modeled [27] as about 10^{-15} cm^2 in the electron energy range $E_e = 5$ to 25 eV. Equation (36) requires an electron density $n_e > 4 \times 10^4$ or 2.3×10^4/cc for $E_e = 5$ or 25 eV, respectively, for the metastable state to play a significant role in CIV of xenon. Such electron densities can be easily met in the ionosphere, even at an altitude near 800 km.

As an estimate of mass loading, we take $n_a \approx 10^5$/cc, $V_A \approx 700$ km/s [34], $M_a(O)/M_b(\mathrm{Xe}) \approx 1/9$, and $V \approx 7.8$ km/s. Taking $s_a = 0.3$ and $s_b = 0.1$, so that $V_r = (1 - s_a - s_b)V = 0.6V = 4.68$ km/s in (29), one obtains $n_b \approx 6.6 \times 10^5$/cc. Since the value of V_* for xenon is about 4.2 km/s, the value of V_r is close to V_*. In view of the possible presence of other intangible factors of energy loss, it is possible that the efficiency of CIV is already near zero at V_r. Therefore, we expect an upper bound of the ionization level of the xenon CIV gas release to be about 6.6×10^5/cc.

XI. Conclusion and Discussion

The purpose of this paper has been to compile some inequality conditions for CIV to occur, which are summarized in Table II, and to explore how these inequalities limit the CIV conditions. For CIV to occur, the beam velocity V must exceed a critical value, V_*, but too high a velocity $V(> V_s)$ may lower the efficiency (eq. (5)). For a diverging neutral beam injected into space, Townsend's criteria I and II (eq. (17)) impose two critical distances, x_1 and x_2; CIV can occur only between these critical distances. The ambient magnetic field in the ionosphere is well within the inequality bounds (eq. (19)). For maximum growth of lower hybrid modes, the parallel wavelength $\lambda_\parallel$ has to fit into the dimension of the interaction region (eq. (21)). This dimension requirement, together with Townsend's criterion II, implies that CIV is likely ruled out at distances (of the order of meters typically) too near the beam origin. Beam angle $\theta = 90°$ may not be optimal (eq. (24)); a smaller angle may allow a longer parallel electron trajectory in the interaction region. For a mixture of species, the critical ionization velocity is not given by the lowest valued species but by an energy budget equation (eq. (25)). Metastable states can foster CIV if the lifetime of the states is long and the electron density is high (eq. (29)). When the beam ionization is too high, mass loading can reduce the efficiency of CIV (eq. (30)). This imposes an upper limit of ionization on beams undergoing CIV in the ionosphere.

Although these inequalities, obtained by using simple models, may be too stringent, they are helpful in providing guidelines for space experiments designed to achieve (or avoid) CIV. We have not included other chemical aspects such as molecular dissociative recombination, ion–molecule reactions, and associative ionization. These processes may influence the progress of CIV, but do not affect in a fundamental way the initiation of CIV.

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